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ABSTRACT

The high strength-to-weight ratio of currently available titanium alloys suggests their use as structural materials for spacecraft components. Six sheet alloys with a 0.2% yield strength of greater than 150,000 psi were welded with nine different filler wire alloys. A combination three-point free- and guided-bend test was used to determine the ductility of the weld joints. Welding after aging resulted in larger fracture deflections and smaller modulus of rupture values than welding prior to aging. On a relative weldability basis the alloys in decreasing order of weldability would be rated: 2.5Al-16V, B120VCA, 6Al-4V, 3Al-6Mo, 4Al-3Mo-1V, and RS140.

I. INTRODUCTION

As structural material for components of high-performance orbiting or space-probe vehicles, the currently available high-strength titanium alloys look promising. At the high-strength levels where the greatest gains are realized, and with the present state of knowledge in the field of fusion welding and heat treating of these alloys, the characteristically low weld ductility is a great handicap.

Reported here is the first phase of a program designed to determine and to improve the weldability of these alloys by studying the effects of the various welding-process variables. This work is concerned with the effects of filler wire composition and the welding heat-treatment sequence on the room-temperature bend properties. Future studies will include the tensile properties and the effects of various heat-treatment and other parameters.

II. ALLOYS INVESTIGATED

The six commercially available high-strength alloys selected for this work are shown in Table 1. Four of the alloys used as the parent metal in this study, i.e., the 2.5Al-16V, B120VCA, 4Al-3Mo-1V, and the 6Al-4V are included in the Department of Defense Titanium Alloy Sheet Rolling Program and were supplied by the Bureau of Weapons of the Department of the Navy. The two other parent metal alloys studied, i.e., the RS140 and the 3Al-6Mo, were included because they have the same strength-level capabilities. All of these alloys were received in the solution-treated condition with a nominal thickness of 0.040 in.

Nine filler wire compositions have been included in this phase of the program. These include the six parent alloy compositions together with the commercially pure Ti75A alloy, the A110AT alloy, and the Ti-3Al alloy. These are also shown in Table 1. Of the filler wires used, the Ti75A, A110AT, Ti-3Al, and 6Al-4V alloys were obtained as 0.060-in.-diameter wire. The other filler wires were made from 1/16-in. strips sheared from the alloy sheets. All wires were cold-swaged to approximately 0.04-in. diameter and then chemically etched to approximately 0.032-in. diameter. The etching solution was used at room temperature and consisted of 4% HF and 40% HNO_3 in water.

The room-temperature tensile properties of the sheet alloys, heat-treated according to the manufacturer's recommendations, are given in Table 2. A 2-in. by 0.5-in. gage section specimen was used to obtain these results. The strain rate was approximately 1×10^{-3}/min to the yield point. Then a crosshead speed of approximately 0.15 in./min was used to fracture.

Since all the sheets were received in the solution-treated condition, the aging treatment shown in Table 2 was the only treatment given prior to testing. This aging was carried out either in a container which was held at approximately 10 μ of mercury with a mechanical pump, or in a sealed container which was evacuated to approximately 0.1 μ and then filled to a slight positive pressure with bottled argon. For these conditions, the cooling rate from the aging temperature was approximately 20°F/min, which is somewhat slower than the air cool recommended by the manufacturers.

The 0.2% yield strength for all alloys was greater than 150,000 psi, and for all but the 3Al-6Mo alloy, the elongation in 2 in. was 4% or greater.

Table 1. Composition of titanium alloys

Nominal alloy composition	Weight percent[a]									
	Al	Cr	Fe	Mo	Sn	V	C	H	N	O[b]
2.5Al-16V	2.49	—	0.22	—	—	15.99	0.03	0.0131	0.014	0.084
B120VCA	4.3	10.4	—	—	—	12.7	0.06	0.0227	0.01	0.044
6Al-4V (sheet)	6.0	—	0.11	—	—	4.1	0.029	0.008	0.008	0.027
3Al-6Mo	3.45	—	0.183	6.13	—	—	0.03	0.0094	0.017	0.038
4Al-3Mo-1V	4.2	—	0.27	3.3	—	1.2	0.04	0.0082	0.018	0.019
RS140	4.90	2.70	1.05	—	—	—	0.031	0.0116	—	0.010
Ti75A	—	—	0.11	—	—	—	0.04	0.0029	0.011	0.009
Ti-3Al	2.9	—	0.03	—	—	—	0.023	0.006	0.007	0.194
6Al-4V (wire)	6.1	—	0.13	—	—	4.0	0.02	0.01	0.017	0.017
A110AT	5.12	—	0.22	—	2.57	—	0.03	—	0.060	0.341

[a]Supplied by producer.
[b]Determined for sheet and wire.

Table 2. Room-temperature tensile properties of heat-treated 0.04 in.-thick titanium alloy sheet

Alloy and nominal sheet thickness, in.	Solution[a] and aging treatment	Longitudinal			Transverse		
		0.2% yield strength ksi	Ultimate tensile strength ksi	Elongation in 2 in. %	0.2% yield strength ksi	Ultimate tensile strength ksi	Elongation in 2 in. %
2.5Al-16V 0.046	1380°F—30 min water-quenched aged at 975°F—4 hr	— 179.9 179.9[b]	191.1 195.1 193.1[b]	5.0 5.0 5.0[b]	175.0 176.0 175.5[b]	186.0 186.0 186.0[b]	5.0 4.5 4.75[b]
B120VCA 0.041	1400°F—30 min air-cooled aged at 900°F—25 hr	178.1 170.5 174.3[b]	196.4 193.0 194.7[b]	6.0 6.5 6.25[b]	178.0 186.0 182.0[b]	191.0 199.0 195.0[b]	4.0 4.0 4.0[b]
6Al-4V 0.036	1660°F—8 min water-quenched aged at 925°F—8 hr	158.0 157.0 157.5[b]	170.0 169.0 169.5[b]	10.5 10.5 10.5[b]	154.0 156.0 155.0[b]	168.0 169.0 168.5[b]	8.5 8.0 8.25[b]
3Al-6Mo 0.043	1550°F—30 min water-quenched aged at 750°F—2 hr; 1000°F—24 hr	168.8 173.5 171.2[b]	184.0 188.0 186.0[b]	1.5 2.5 2.0[b]	172.0 176.0 174.0[b]	184.0 184.0 184.0[b]	2.5 3.5 3.0[b]
4Al-3Mo-1V 0.040	1650°F—15 min oil-quenched aged at 925°F—12 hr	156.5 157.6 157.1[b]	190.5 190.5 190.5[b]	7.5 8.5 8.0[b]	158.0 157.0 157.5[b]	191.0 190.0 190.5[b]	7.0 7.0 7.0[b]
RS140 0.048	1520°F—6 min water-quenched aged at 900°F—6 hr	159.0 159.9 159.5[b]	197.1 197.7 197.3[b]	6.5 6.7 6.6[b]	166.0 169.0 167.5[b]	208.0 208.0 208.0[b]	6.0 6.0 6.0[b]

[a]All sheets solution-treated by producer.

[b]Average.

III. WELDING PROCEDURE

For this investigation the automatic inert-gas-shielded tungsten-arc process was used. The filler wire was automatically fed into the arc of a non-consumable tungsten electrode. The welding-process parameters used are given in Table 3. Details of the welding fixture are shown in Fig. 1.

Since the welding torch travel speed and the wire feed are important factors in controlling the dilution of the parent metal during welding, these parameters were carefully controlled to the values given in Table 3. Since all sheets were nominally of the same thickness, a constant welding current could be used without greatly affecting the width of the weld zone, which was approximately 3/16 in. on the top surface.

To prevent contamination and to insure a bright weld zone, gas shielding, in addition to that provided by the welding cup and the back-up groove, was provided by a 4½-in.-long by 2-in.-wide trailing shield with a porous

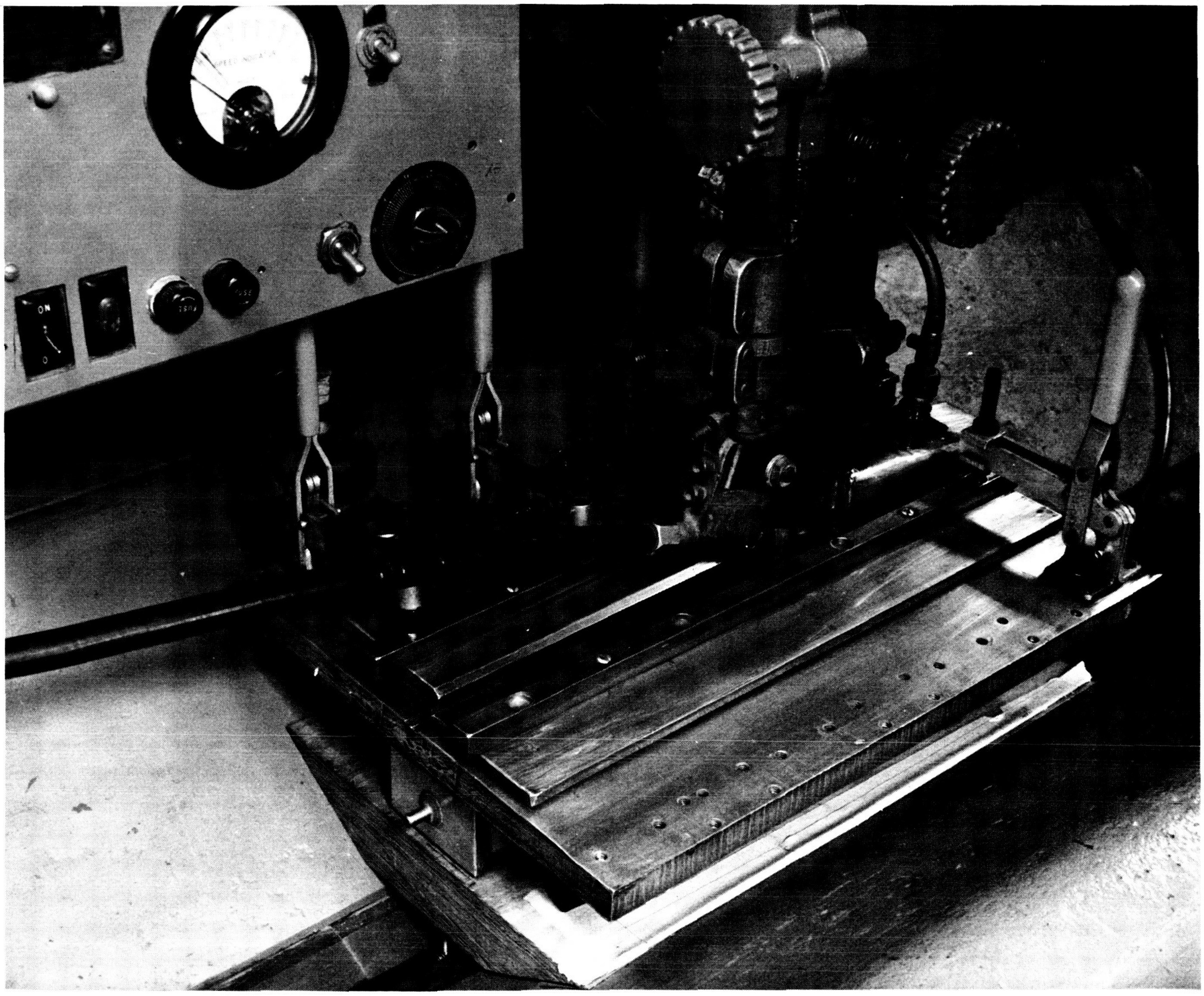

Figure 1. Welding fixture for 0.40-in.-thick titanium alloy sheet (Some of the hold-down clamps have been removed for clarity.)

Table 3. Procedures for welding titanium alloy sheet

Components	Method and/or setting	Components	Method and/or setting
Joint type	Machined-edge butt joint	Wire feed	18 in./min
Joint cleaning	Abrade with steel wool, degrease with acetone	Wire size	0.032 ± 0.005-in. diameter
Joint backing	Uncooled grooved copper plate, with 0.030-in. by 0.375-in. groove	Torch and cup	Commercial, water-cooled copper cup 0.75-in. ID on A HW-13 welding torch
Torch gas flow	30 cfh of helium	Electrode	Pointed 0.040-in. diameter thoriated tungsten, ¼-in. extension from torch cup
Back-up gas flow	7 cfh of argon		
Trailing-shield gas flow	25 cfh of argon	Arc voltage	20 dc
Torch travel	14 in./min	Arc current	30 amp, straight polarity

bronze diffusion plate. A chemical analysis of test welds in the 2.5 Al-16V alloy gave oxygen contents of 0.08% and nitrogen contents of 0.017%, which are comparable to the interstitials in the as-received sheet (Table 1). It was therefore assumed that the welding procedure used did not contaminate the weld joint.

IV. BEND-TESTING PROCEDURE

To provide a preliminary evaluation of the various combinations of alloy and filler wire as well as heat-treatment welding sequence, a simple room-temperature bend test was used. This was a combined three-point free- and guided-bend test and used the equipment shown in Fig. 2. It consisted of a 105-deg "V" wedge with a 0.124-in. radius, which bent the test specimen in a 105-deg "V" block with a span of 4 in. The bending force was

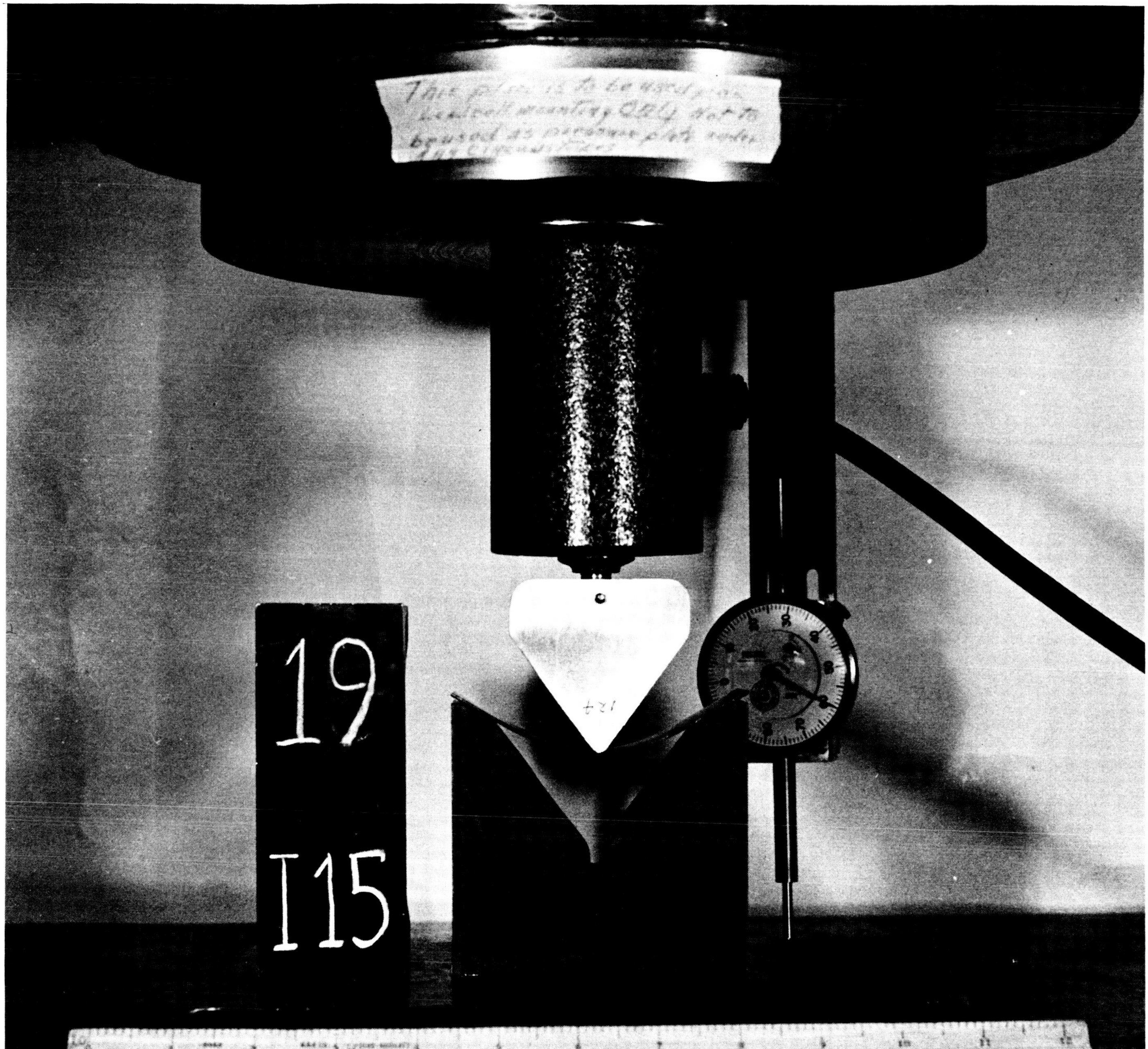

Figure 2. Bend-testing equipment

recorded continuously as the output of the load cell. The deflection was determined by a dial gage which measured the relative movement of the testing-machine crossheads.

The test specimen was 4½-in. by 1½-in. by sheet thickness, with the weld located at the mid-width of the specimen parallel to the 4½-in. dimension and also parallel to the sheet-rolling direction. The specimens were taken from 3-in. by 14-in. weld panels. Each panel was radiographed to insure that no defects were present in the test specimen. The weld reinforcement was removed prior to testing, and the top of the weld was on the tension side of the bend specimen.

A bend test of this type is particularly well suited for evaluating the ductility of weld joints since it requires each part of the joint to undergo the same deformation and is simpler to make than a tension test with the weld in the longitudinal direction. The combined free- and guided-bend test differs from a free-bend test in that the deflection is continued beyond the point of maximum load for a free-bend test and on into the region of a guided-bend test. In such a test the total deflection prior to fracture is an indication of the ductility of the specimen. Thus, in this bend test the deflection prior to fracture was used to evaluate the ductility of each weld joint, and the maximum free-bend load was used to calculate the modulus of rupture, which is an indication of the strength.

In using the results of this type of test to compare various welds, caution must be used since the fracture deflection values may reflect differences in the strength level, the modulus of elasticity, the thickness, and the residual stress in the specimen.

V. RESULTS

For a clearer understanding of the results obtained during this investigation, the effects of the filler wire composition and of the welding heat-treatment sequence will be discussed separately.

A. Effect of Filler Wire Composition

The load-deflection curves obtained during the bend-testing of the unwelded, solution-treated and aged alloys are shown in Fig. 3-8. The load increased with the deflection until the maximum free-bending load was reached, and then decreased as the specimen deformed plastically. As the deformation was continued and the specimen was forced to conform to the shape of the bending fixture, in a guided-bend test manner, the load was increased until fracture occurred or until the test fixture bottomed, at which point the test was discontinued.

The general shape of the load-deflection curves for the welded specimens was the same as for the unwelded specimen, except for the deflection at fracture. For this reason, not all of the curves have been shown. Instead, the fracture deflection for each filler wire for the solution-treated, welded, and aged condition has been indicated on the load-deflection curve for the unwelded, aged parent metal (Fig. 3-8). The fracture deflection values, as well as the rupture modulus values for all specimens, are given in Table 4.

The results show that for a given parent metal, this test effectively demonstrates the differences in weld-joint ductility caused by the various filler wires. This is clearly indicated in Fig. 3, which shows results obtained with the 2.5Al-16V alloy. The weld joint made with the B120VCA filler wire fractured shortly after the maximum free-bend load was reached, and therefore exhibited very little ductility. The weld joints made with the Ti75A and the Ti-3Al filler wires did not fracture until a deflection almost equal to the fracture deflection of the unwelded parent metal was reached. Other filler wires

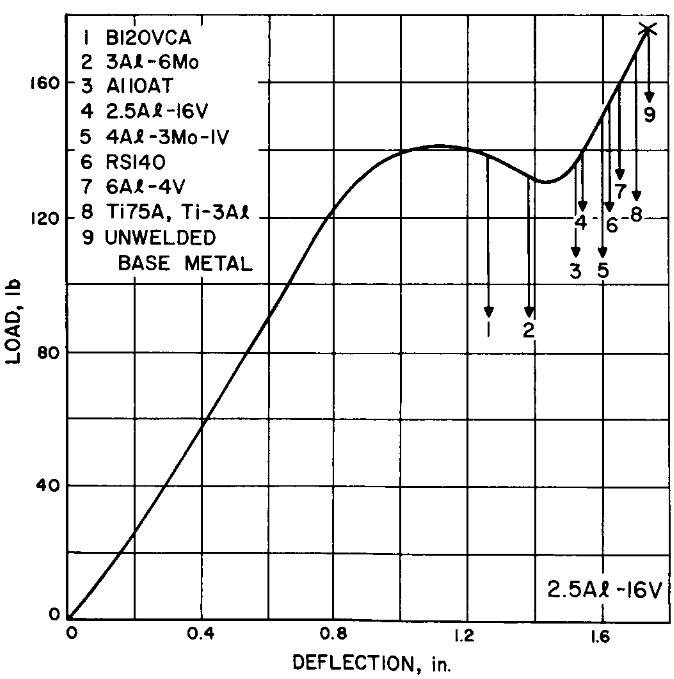

Figure 3. Load-vs-deflection curve for 2.5Al–16V titanium alloy*

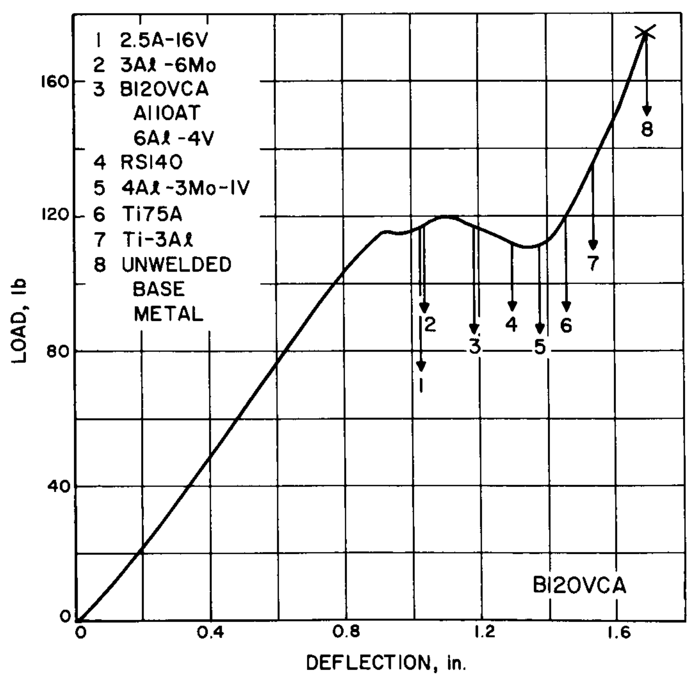

Figure 4. Load-vs-deflection curve for B120VCA titanium alloy*

*The curve shown is for the unwelded parent alloy in the solution-treated and aged condition. The vertical lines indicate the fracture deflection for welded joints made with the filler wires indicated and tested in the solution-treated, welded, and aged condition.

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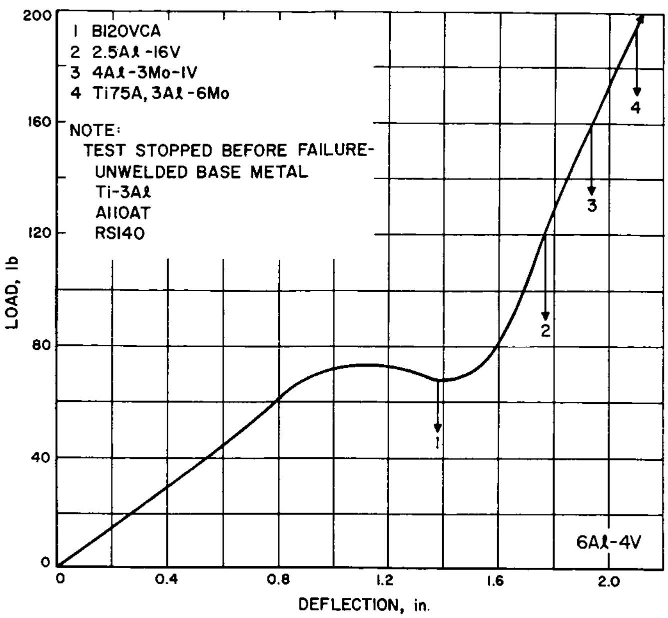

Figure 5. Load-vs-deflection curve for 6Al–4V titanium alloy*

*The curve shown is for the unwelded parent alloy in the solution-treated and aged condition. The vertical lines indicate the fracture deflection for welded joints made with the filler wires indicated and tested in the solution-treated, welded, and aged condition.

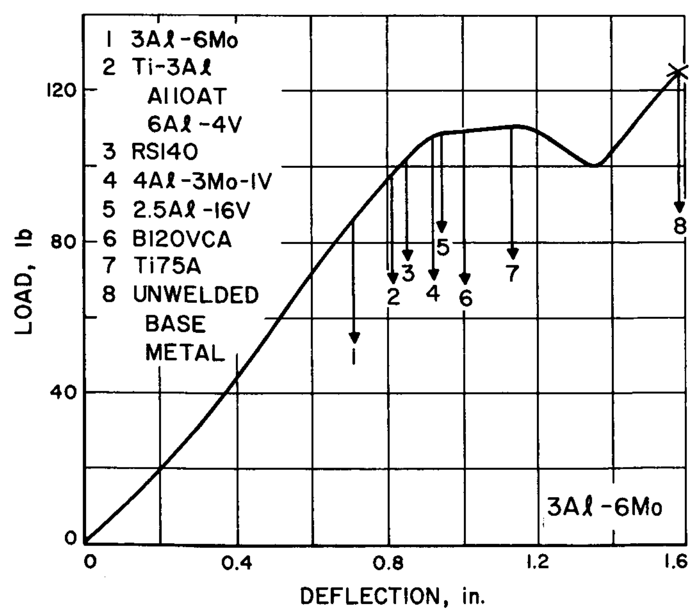

Figure 6. Load-vs-deflection curve for 3Al–6Mo titanium alloy*

*The curve shown is for the unwelded parent alloy in the solution-treated and aged condition. The vertical lines indicate the fracture deflection for welded joints made with the filler wires indicated and tested in the solution-treated, welded, and aged condition.

produced welded joints with intermediate fracture deflections.

For a few tests, as noted in Table 4, the welded test specimen was distorted so as to give a slightly different shape to the initial portion of the load-deflection curve. In these cases, it was necessary to correct the actual measured fracture deflection to eliminate the effects of this distortion. In no case was this correction large enough to affect the final rating of any of the filler wires.

A study of these results indicates that the composition of the filler wire has some effects which are common to all the alloys tested, in that the larger fracture deflections were associated with the lower alloy filler wires. However, in all but the 6Al-4V alloy (Fig. 5) even the most ductile weld joints resulted in fracture deflections which were smaller than the unwelded deflections.

The data also permit a rating of the alloys in terms of relative weldability. From the curves it can be seen that for the RS140 alloy (Fig. 8), most of the weld joints fractured before the maximum elastic load was reached,

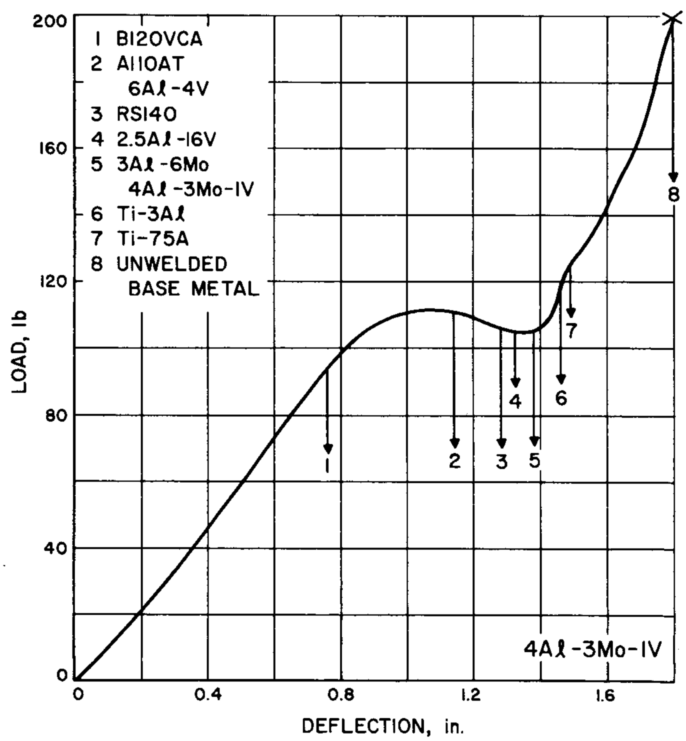

Figure 7. Load-vs-deflection curve for 4Al–3Mo–1V titanium alloy*

*The curve shown is for the unwelded parent alloy in the solution-treated and aged condition. The vertical lines indicate the fracture deflection for welded joints made with the filler wires indicated and tested in the solution-treated, welded, and aged condition.

Table 4. Room-temperature bend properties of weld joints in heat-treated titanium alloy sheet

Filler wire nominal composition	2.5Al-16V aged 975°F—4 hr				B120VCA aged 900°F—25 hr				6Al-4V aged 925°F—8 hr			
	Solution-treated, welded, aged		Solution-treated, aged, welded		Solution-treated, welded, aged		Solution-treated, aged, welded		Solution-treated, welded, aged		Solution-treated, aged, welded	
	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi
Unwelded base metal	1.74	283.9	1.74	283.9	1.70	286.3	1.70	286.3	2.08[b]	235.0	2.08[b]	235.0
Ti75A	1.7	235.7	1.69	217.8	1.46	247.7	1.55	227.9	2.10	234.6	1.84	219.1
Ti-3Al	1.7	—	1.74	218.2	1.54	268.1	1.66	239.4	2.26[b]	230.5	1.82	223.1
6Al-4V	1.65	246.6	1.74	215.7	1.28	270.1	1.70	210.4	—	233.0	1.82	229.9
RS140	1.62[a]	253.6	1.71	215.7	1.30[a]	292.2	1.52	248.5	2.22[b]	257.8	1.78	221.9
4Al-3Mo-1V	1.60	262.3	1.74	209.1	1.54	267.9	1.62	225.0	1.94	249.8	1.68	225.8
25Al-16V	1.54	245.2	1.76	213.6	1.02[a]	278.6	1.59	215.4	1.77	233.0	1.62	227.1
A110AT	1.52	283.3	1.74	216.2	1.28	286.5	1.60	230.6	2.24[b]	236.7	1.82	221.2
3Al-6Mo	1.38	262.3	1.70	219.7	1.04	267.1	1.58	235.8	2.10	244.9	1.82	234.7
B120VCA	1.26	257.2	1.78	215.7	1.28	231.2	1.58	230.8	1.38	226.8	1.73	229.7

Filler wire nominal composition	3Al-6Mo aged 750°F—2 hr; 1000°F—24 hr				4Al-3Mo-1V aged 925°F—12 hr				RS140 aged 900°F—6 hr			
	Solution-treated, welded, aged		Solution-treated, aged, welded		Solution-treated, welded, aged		Solution-treated, aged, welded		Solution-treated, welded, aged		Solution-treated, aged, welded	
	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi	Fracture deflection in.	Rupture modulus ksi
Unwelded base metal	1.58	286.8	1.58	286.8	1.80	278.8	1.80	278.8	1.78	302.9	1.78	302.9
Ti75A	1.16	245.0	1.62	251.5	1.48	254.2	1.53	255.3	1.20	249.4	1.63	260.4
Ti-3Al	0.80	249.2	1.62	243.1	1.46	240.4	1.58	245.3	1.06	—	1.48	267.3
6Al-4V	0.80	231.4	1.54	246.2	1.24	261.0	1.42	254.5	1.15	278.0	1.49	266.2
RS140	0.84	241.4	1.52	251.1	1.28	252.8	1.39	235.1	0.86	273.1	1.34	268.8
4Al-3Mo-1V	0.92	249.5	1.56	255.8	1.36	256.1	1.50	253.6	0.88	289.3	1.48	272.5
25Al-16V	0.88	243.1	1.54	247.8	1.32	257.9	1.59	246.6	0.92	290.1	1.55	251.4
A110AT	0.80	220.1	1.18	249.9	1.24	250.7	1.56	246.0	1.03	286.4	1.16	260.8
3Al-6Mo	0.76	232.7	1.56	241.9	1.36	254.0	1.50	237.7	0.92	264.3	1.08	275.4
B120VCA	0.98	263.7	1.60	213.9	0.76	239.8	1.68	231.9	0.69	238.7	1.63	256.5

[a] Value corrected for specimen warpage.
[b] No fracture, test discontinued.

thus indicating low ductility. For the 2.5Al-16V alloy (Fig. 3), all of the weld joints fractured after the maximum elastic load was reached, indicating greater ductility.

A more quantitative method for rating the alloys is a comparison of the fracture deflection of the most ductile weld joint of each alloy with the fracture deflection of the unwelded parent material. The results obtained by using this method are given in Table 5. It is important to point out that caution should be employed in using this method of comparison to rate various materials. Such a rating could be affected by the magnitude of the fracture deflection of the unwelded parent metal, by the modulus of elasticity of the material, and by the thickness of the test specimen. Since all of these fall into rather nar-

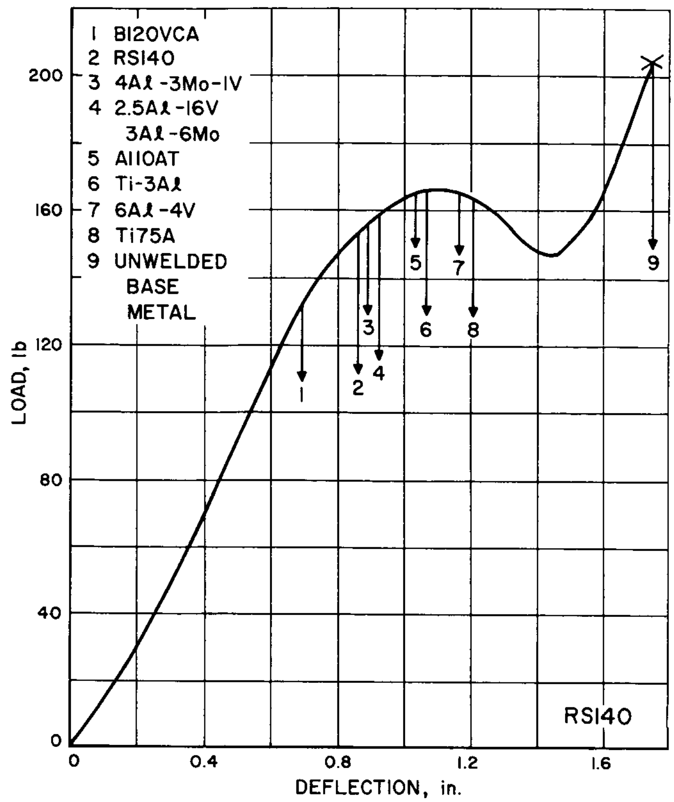

Figure 8. Load-vs-deflection curve for RS140 titanium alloy*

*The curve shown is for the unwelded parent alloy in the solution-treated and aged condition. The vertical lines indicate the fracture deflection for welded joints made with the filler wires indicated and tested in the solution-treated, welded, and aged condition.

row limits for the alloys shown in Table 5, the comparisons seem reasonable. In any rating of these alloys, consideration must also be given to the strength of the parent metal, which is also shown in Table 5.

B. Effects of Welding Heat-Treatment Sequence

The effects of welding before or after the aging treatment may be determined by comparing the fracture deflections shown in Table 4. For all the alloys studied, except the 6Al-4V, welding after aging without further heat treatment resulted in higher fracture deflections than welding prior to the aging treatment. This greater ductility probably reflects the presence of a softer, unheat-treated weld zone, as is borne out by the generally lower modulus of rupture values for the solution-treated, aged, and welded specimens (Table 4). It is also possible that such welds may contain a metastable zone which could easily be embrittled.

Table 5. Relative weldability of heat-treated titanium alloy sheet

Nominal composition of alloy	Base metal ultimate strength ksi[a]	Welding–heat-treating sequence	Relative weldability[b]
2.5Al-16V	179.9	Solution-treated, welded, aged	0.98
		Solution-treated, aged, welded	1.0
B120VCA	174.3	Solution-treated, welded, aged	0.91
		Solution-treated, aged, welded	1.0
6Al-4V	159.5	Solution-treated, welded, aged	1.0
		Solution-treated, aged, welded	0.88
3Al-6Mo	171.2	Solution-treated, welded, aged	0.73
		Solution-treated, aged, welded	1.0
4Al-3Mo-1V	157.1	Solution-treated, welded, aged	0.82
		Solution-treated, aged, welded	0.93
RS140	159.5	Solution-treated, welded, aged	0.67
		Solution-treated, aged, welded	0.92

[a]Longitudinal.

[b]Relative weldability $= \dfrac{\text{fracture deflection of most ductile weld joint}}{\text{fracture deflection of unwelded base metal}}$.

The load-deflection curves recorded for the solution-treated, aged, and welded specimens were of the same general shape as those shown in Fig. 3-8, except that the maximum free-bend load was somewhat lower because of the lower modulus of rupture.

It is possible that a heat treatment could be used prior to the welding process which would not show the effects of welding after aging as reported here. Since this work was a preliminary study, it was not within its scope to investigate the various heat treatments.

VI. CONCLUSIONS

The results of this preliminary study may be summarized as follows:

1. A combined three-point free- and guided-bend test which required an easy-to-prepare test specimen was used to evaluate the ductility of various base metal-filler wire combinations in weld joints of high-strength heat-treatable titanium alloys.

2. For all the parent alloys studied, the weld joints made with the low-alloy filler wires were more ductile at room temperature than those made with the higher-alloy filler wires.

3. For all alloys studied, except the 6Al-4V, welding after aging with no further heat treatment gave weld joints of greater ductility but of lower rupture modulus than welding prior to the aging treatment.